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OPTIMIZATION OF STABILIZED IMPLODING LINER FUSION REACTORS.(U)

JUN 79 P J TURCHI, D L BOOK, R L BURTON

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Optimization of Stabilized Imploding Liner Fusion Reactors

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Plasma Physics Division

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In the NRL LINUS concept for controlled fusion systems, a rotating liquid metal cylinder or liner is imploded onto a trapped plasma/magnetic field payload to obtain fusion temperatures and near-megagauss magnetic field levels by adiabatic compression. The combined use of liner rotation and a free-piston driving technique eliminates Rayleigh-Taylor instabilities and permits safe, repetitive implosion-reexpansion cycles. Optimization of system size is accomplished in terms of the implosion radius-ratio and liner compressibility. Trade-offs between reactor size and initial plasma temperature are indicated.

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CONTENTS

OPTIMIZATION OF STABILIZED IMPLODING LINER FUSION REACTORS

I. Introduction

The use of imploding liner magnetic flux compression techniques {1,2} to achieve fusion plasmas at megagauss magnetic field levels has been of interest for almost two decades {3,4}. A basic problem has been the destructiveness associated with the high kinetic energy, electrically conducting shells or liners required for magnetic flux compression. Over the last few years, efforts at the Naval Research Laboratory, in a program called LINUS, have been successful in eliminating this problem {5,6,7}. A new class of pulsed, controlled fusion reactor may therefore be possible {8,9} offering potential advantages over conventional fusion reactor designs.

II. LINUS Concept

The basic geometry of a LINUS-type imploding liner fusion system consists of a high beta plasma/field mixture separated from a surrounding, electrically conducting cylinder by a region of high magnetic field and low plasma

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density. Implosion of the cylindrical liner compresses the plasma adiabatically and simultaneously increases the confining magnetic field by flux compression. To avoid severe losses to resistive diffusion and plasma heat conduction during such compression of magnetic flux and plasma, the liner implosion radius and speed are typically tens of centimeters and tens of thousands of cm/sec, respectively. If the dynamics of the liner material are not closely controlled, considerable destruction of the local apparatus can be incurred, severely diminishing the chances of developing liner implosion systems into fusion power reactors.

To achieve the necessary degree of control, not only must the basic motion of the liner material be reversible, requiring liquid liners, but hydrodynamic instabilities must also be eliminated. During the final stages of plasma compression, if liner kinetic energy is efficiently transferred to the plasma/field payload, the interface between the high mass density liner and the low mass density payload will be subject to Rayleigh-Taylor instability. Growth of perturbations due to such instability can result in destruction of the fusion temperature plasma by injection of liner material into the plasma. If the liner is initially given sufficient angular momentum, properly distributed, so that the centripetal acceleration, v_θ^2/r, exceeds the kinematic acceleration, d^2r/dt^2, at peak compression, then Rayleigh-Taylor instability at the inner surface of the liner will be eliminated {7,10,11,12}.

The outer surface of the liner will also be subject to Rayleigh-Taylor instability as it is accelerated by a lower mass density driving medium (magnetic field or high pressure gas). Rotation cannot help in this case. It is necessary to eliminate the free outer surface of the liquid liner, driving the implosion and slowing the reexpansion of the liner by means of a free-piston in continual contact with the outer surface. The combined use of rotation and free-piston drive to obtain completely stabilized, repetitive implosion-reexpansion cycles has been demonstrated in hydrodynamic model experiments {5,6,7}. Large radius-ratio (12 to 30:1) implosions of excellent quality and efficiency have been achieved by these techniques.

A consequence of the free-piston drive is that the ratio of liner thickness to the plasma radius at peak compression will approximately equal the radial compression ratio. In reactor-level systems, as noted below, the liner thickness will be sufficient to absorb essentially all the neutron energy flux from the reacting plasma and to provide an adequate breeding ratio for tritium in lithium-bearing liners. The liner thus serves as the reactor blanket and first-wall protecting the permanent portion of the reactor from high energy neutron damage, reducing radioactivity, and greatly simplifying reactor servicing. The continuous flow of liner material through the reactor allows extraction of tritium, and heat due to neutron deposition, plasma radiation, resistive diffusion and friction. The potential simplicity of LINUS-type reactors in terms of plasma heating (adiabatic compression) and operation of first-wall and blanket material (the liner itself) may offset the possible problems of pulsed, high pressure mechanical operation.

III. Optimization Studies

An additional consequence of relatively thick liners associated with the free-piston driving technique is that final compression of the payload can occur on a timescale shorter than that for soundwave transit through the liner. This reduces the efficiency of energy transfer to the payload as some energy will remain in liner kinetic energy and/or be stored in compression of the liner material itself. While the nuclear energy gain, Q, relative to the total system energy will increase with higher peak payload pressures, P_f, the rate of increase drops sharply for values of a normalized pressure parameter $\zeta_f \equiv P_f/\rho c^2$ (ρ = liner mass density, c = liner sound speed) greater than about 0.12 {13}.

By equating the work done in displacing the piston to the system energy at peak compression, the effective driving pressure may be written as $\bar{P} = \lambda\rho c^2\zeta_f/\alpha^2\varepsilon(\alpha,\zeta_f)$, where λ is a constant depending on the properties of the driver system, α is the radial compression ratio of the liner surface and $\varepsilon(\alpha,\zeta_f)$ is the ratio of payload energy to total energy. Since $\varepsilon(\alpha,\zeta_f)$ is a monotonically decreasing function of ζ_f, $\bar{P}$ increases rapidly with ζ_f. If the allowable working stress, S, is fixed (and $\bar{P}/S \lesssim 0.375$), the thickness of the implosion chamber containing the pulsed, high pressure liquid liner will increase approximately linearly with $\bar{P}$. The total system radius can then be written as $r_T = gr_2 (1 + \bar{P}/S)$, where r_2 is the initial radius of the liner surface, and g is a geometric factor depending on the free-piston drive mechanism. In Fig. 1, the nuclear energy gain Q_p relative to the payload energy, and the gain Q relative to the total system energy are compared with r_T as a function of ζ_f and α. The parameter $\Sigma^* = \lambda\rho c^2/S$ is chosen to correspond approximately to a lead-lithium liner ($\rho \approx 10.6$ gr/cm^3, $c \approx 1.6 \times 10^5$ cm/s) with an allowable chamber stress $S = 6.8 \times 10^8$ dyne/cm^2, and $\lambda = 1.5$. The geometric factor g is assumed to be two. The solid curves are for an axially-displaced annular piston drive {5,6} in which the flow channel partially supports the pressure forces on the chamber. The broken lines are for radial-displacement piston drives in which such support is absent.

Optimum operating values for ζ_f are indicated and a reduction in size with lower values of α is also suggested. To good approximation, the minimum values of the total system radius for Q = 1.5 are given (in cm.) by $r_T = 16.5\ \alpha$. (For a scientific feasibility experiment, $Q_p = 1$, the variation of r_T with α is much weaker).

Low values of α, however, restrict the radial compression of the plasma to still lower values. Since the nuclear gains computed are based on peak temperatures, T_f, about equal to 15 keV or higher, if the compression ratio is too low, the required initial plasma temperature may be quite high. The initial plasma temperature may be written as $T_i = T_f(\alpha_i/\alpha)^{2(\gamma-1)}$, where α_i is the radial compression of the liner prior to plasma compression. For purely cylindrical compression of the plasma and with an adiabatic exponent $\gamma = 5/3$, $T_i = T_f\ (\alpha_i/\alpha)^{4/3}$. (The actual behavior of the plasma/field payload during compression {14} may result in an effective adiabatic exponent of 1.8, in which case $T_i = T_f\ (\alpha_i/\alpha)^{1.6}$).

The initial plasma temperature, liner radius, and implosion speed must be sufficient to allow plasma heating against various loss processes, of which the principal (in closed-field systems) is ion crossed-field thermal conduction. If classical scaling is assumed, then the conduction loss time is proportional to $r_i^2\ T_i^{3/2}$, and its ratio to implosion time, r_i/u_i, scales simply as $r_i u_i T_i^{3/2}$, where r_i and u_i are the liner radius and speed, respectively, at the time the plasma payload is formed. From recent numerical computations {7,15} including anomalous transport coefficients due to micro-instabilities, acceptable values of $r_i u_i T_i^{3/2}$ might range from 0.2 to 3 x 10^9 {cm^2 - sec^{-1} - $eV^{3/2}$}.

For the initial stages of implosion, the simple mechanics of an incompressible liner, based on equating driver pressure work with liner kinetic energy, gives $u_i = \{(\alpha_i^2-1)/(\ln\alpha_i + A_i)\}^{1/2} (\bar{P}/\rho)^{1/2}$, where A_i is a constant about equal to unity for axial-displacement drives. With $\bar{P}$ = 0.375 S, and A_i = 1, the minimum initial plasma temperature may be found as a function of α by equating T_i required for thermal loss reduction (with $r_i u_i T_i^{3/2} = 10^9$) to that required for compression to a peak temperature of 15 keV. Values are given in Table I, for Q = 1.5, S = 6.8 x 10^8 dyne/cm^2, γ = 5/3 and other parameters as before. (Numbers in parentheses are for γ = 1.8.)

Summary Remarks

From Table I, it can be seen that lower values of liner compression ratio require substantially higher initial plasma temperature. While the creation inside liners of plasmas with initial temperatures of a few hundred eV might be possible using plasma gun technology {7} or

Table I

Initial Plasma Temperature T_i and Liner Thickness Δr at Peak Compression Versus Liner Compression Ratio α

α	α/α_i	T_i {eV}	Δr {cm}
10	9.8 (9.2)	715 (431)	54
20	18.9 (14.8)	298 (201)	114
30	27.2 (18.2)	183 (145)	174

electron beams {14}, extrapolation to near-kilovolt levels will certainly be more difficult. At this time, however, definitive results on the generation of plasma for compression by liner implosion are not available. Trade-offs between system size and initial plasma temperature cannot, therefore, be made yet with any precision. Preliminary nucleonics studies of lead-lithium liners {16}, however, indicate that the liner thickness Δr at peak compression should be at least 110 cm. Thus, from Table I, it appears that liner compression ratios of at least twenty will be desirable, corresponding in Fig. 1 to optimum normalized pressures ζ_f of about 0.09, and a total system radius of about 3.3 meters.

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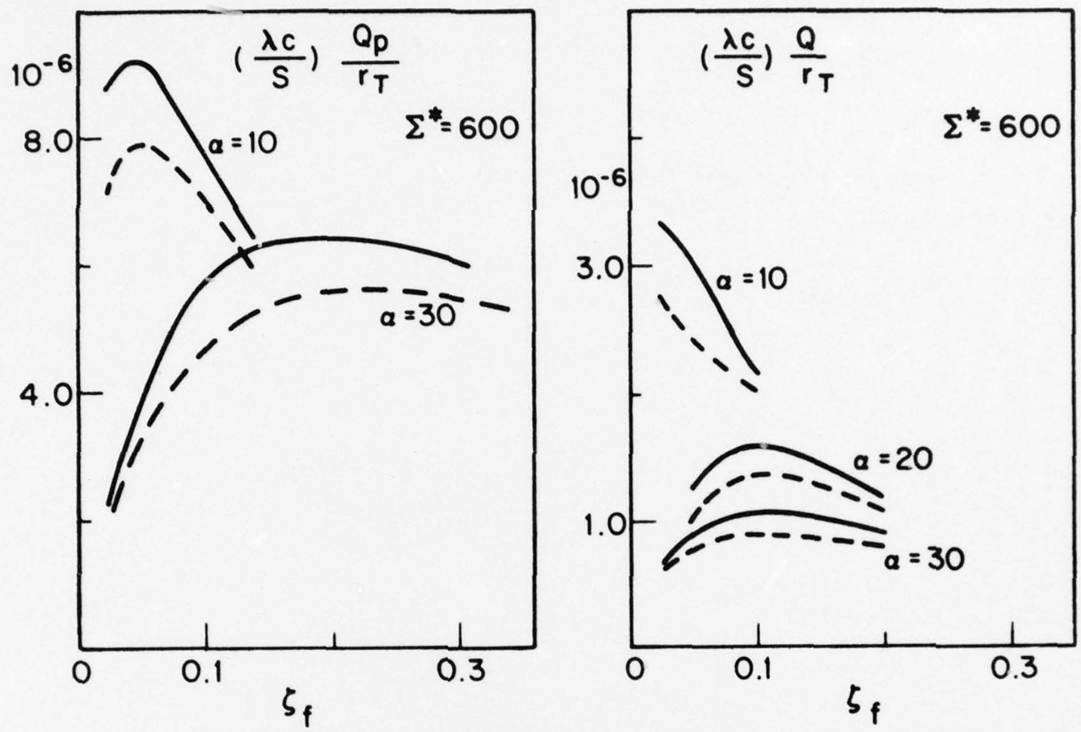

Fig. 1 Fusion Gain Related to System Radius Versus Normalized Peak Pressure ζ_f. Units for $\lambda c/Sr_T$ are $\{cm^2\text{-}dyne^{-1}\text{-}\ sec^{-1}\}$. Q_p is gain relative to payload energy; Q is gain relative to total system energy.